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13. ABSTRACT (Maximum 200 words) High temperature superconducting Josephson arrays were investigated as possible millimeter wave sources. A junction technology was selected and improved to the point where radiation, near 1 microwatt off-chip, was measured from a variety of 2-dimensional arrays in the 70-160 GHz range. The arrays were tunable and were successfully coupled to a number of antennas for broadband, tunable transmission. Antennas for a variety of specific applications were selected on the basis of bandwidth requirements, impedance levels, polarization, and the possibility of sufficient monolithic integration. The final part of the program was a study of potential subsystems that would utilize these arrays. Interchip communications transceivers were studied and interchip coupling was demonstrated using two antenna-coupled arrays. The most promising application may be a monolithic clock source, near 100 GHz, for communications and signal processing systems.					
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## PHASE I FINAL REPORT

CONTRACT F49620-93-C-0041

# HIGH TEMPERATURE SUPERCONDUCTING JOSEPHSON JUNCTION ARRAY SYSTEMS

## EXECUTIVE SUMMARY

This goals of this Phase I program were to investigate high-temperature superconducting Josephson arrays as mm-wave sources, to demonstrate radiation from them if possible, to investigate potentially compatible radiative structures and to study practically useful subsystems that would utilize their features. A junction technology was selected and improved to the point where radiation from a variety of 2-dimensional arrays was measured. Power outputs of near 1  $\mu$ W were measured, off-chip, and calibrated, above 100 GHz. The arrays were functioning and were successfully coupled to a variety of antennas for broadband transmission. The effects of array topology on radiation were investigated and an appropriate structure selected for further development. Antennas for a variety of specific applications were selected on the basis of bandwidth requirements, impedance levels, polarization and capability of sufficient monolithic integration. The final part of the program was a study of potential subsystems that would utilize these arrays. Interchip communications transceivers were one application studied and interchip coupling was demonstrated using two of the antenna coupled arrays. The most promising of the applications appears to be a monolithic clock source operating near 100 GHz. A monolithic source of clean signals in this frequency range would solve many skewing and power distribution problems beginning to appear in higher performance signal processing and communications circuits. Based on the demonstrated performance of simple arrays, the feasibility of applications such as the clock, and the inherent advantages of arrays in terms of efficiency, size and tunability make continuing work very attractive.

1. Background and objectives

The purpose of this Phase I project was to begin an investigation of high-temperature superconducting Josephson junction arrays as mm-wave sources for a variety of possible applications. Many existing sources in this frequency range suffer from low power density, poor efficiency and/or difficult integrability [1]. The fundamental advantages of Josephson arrays [2] could be important in these applications areas if significant phase locking of a sufficiently large arrays can be achieved to obtain useful power levels

The objectives for this Phase I project can be grouped into five areas

## 1. Assessment of junction technologies for array purposes

We have two main junction technologies in house and the best one was to be selected for further array development. Criteria include  $I_c$ ,  $R_n$ ,  $\Delta I_c$ ,  $\Delta R_n$ , yield and process ease.

## 2. Process improvements

This is not a major component but the junction and other process steps were to be improved particularly with respect to parameter uniformity. This was in conjunction with larger efforts on other programs.

## 3. Test process run

Fabricate simple arrays and other circuits to help evaluate junction processes, passive structures and to attempt radiation measurements on some simple arrays.

## 4. Radiative element study

A paper study (with simple experiments when feasible) of appropriate antenna types (bow, planar equiangular and Archimedian spirals and log periodic spirals) that are all broadband but have differences in impedance levels, bandwidth, polarization and other factors.

## 5. Subsystem integration study

A look at possible applications (that may be exploited in phase II) including source-based concepts, mm-wave transceivers and junction arrays as phased array systems.

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## 2 Status of research effort

Radiation was successfully measured from HTS JJ arrays during this project [3],[4] after preliminary tests and improvements on the junction processes. The effects of topology on radiation were analyzed and a probable structure was selected for later work. Paper studies were conducted on radiation structures and subsystem applications. Likely radiative structures were selected for several applications and the applications were graded on technical feasibility and economic interest.

### 2.1 Junctions:

Two types of junctions were analyzed for use in the arrays project: electron-beam-defined nanobridge junctions (NBJ) [5] and SNS edge junctions [6]. The structure and fabrication of these junctions have been discussed in the literature and in the Phase I proposal. As can be seen from the following table, the NBJs have a definite advantage in terms of uniformity but have generally smaller critical currents and a longer fabrication time. The low critical current can be compensated for by paralleling a number of junctions (as has been done for some digital circuits), but the penalty in area can be enormous for array applications. For these purposes, yield is defined as the fraction of junctions on a wafer having critical current  $> 5 \mu\text{A}$  and it generally exceeded 90% for both types of junctions.

Junction Type	$I_c$ ( $\mu\text{A}$ )	$R_n$ ( $\Omega$ )	$\Delta I_c$ ( $3 \sigma$ )	$\Delta R_n$ ( $3 \sigma$ )	yield	lithography difficulty	process time
SNS	100-500	0.2-2	$\pm 22\%$	$\pm 12\%$	high	easy (2 $\mu\text{m}$ )	short (3-5 days)
NBJ	20-70	5-20	$\pm 11\%$	$\pm 7\%$	high	hard (e-beam)	long (1-4 weeks)

The reduction in power density (array power per unit lithographic area) using NBJs can be severe and may not be acceptable for the source-based applications. The long lead time at this point is primarily an inconvenience. Also, although the SNS spreads are poorer, they are improving with new barriers being engineered. The substitution of Co- and Ca-doped YBCO barriers for the

original  $\text{CaRuO}_3$  barrier have reduced interface resistances and associated critical current variations [6]. For these reasons, we chose to pursue primarily the SNS arrays for this work.

## 2.2 Process improvements:

Although this was not a significant part of this program (most of the work is being performed in other programs which are being leveraged), the barriers were re-engineered this year resulting in improved SNS uniformity. Improvements were also made in design rules allowing a tighter packing of junction within the arrays thus increasing power density. This change was made possible by changes in the ion milling protocol.

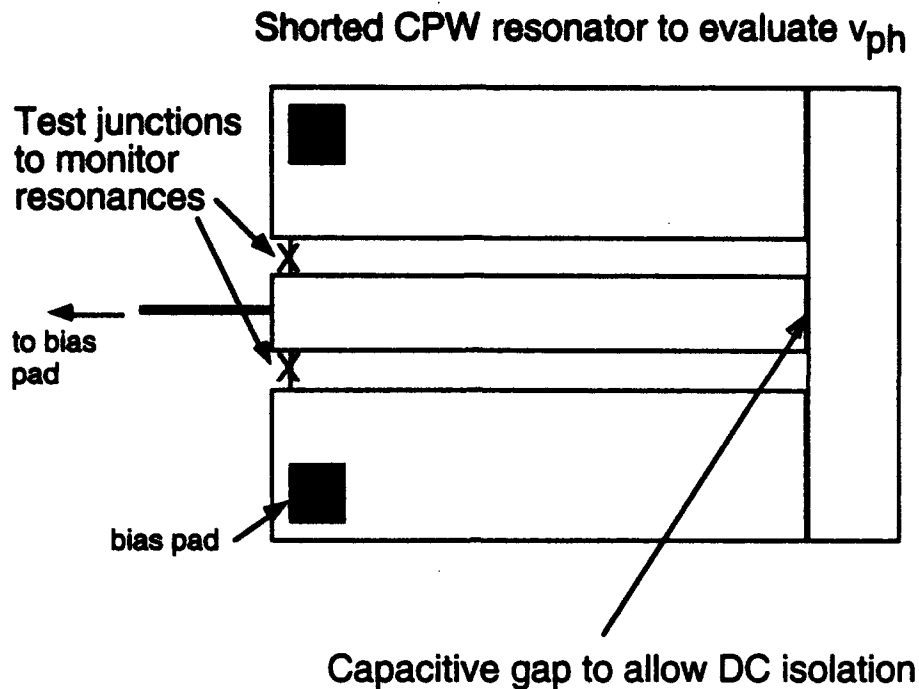
## 2.3 Test fabrication and measurement results

Two types of chips were fabricated under the auspices of this contract. The first consisted of a variety of 2-D array topologies (plus test structures). These arrays were designed for dc and spectral (off-chip) measurements. These measurements are used to study linewidth, efficiency, output power and topological dependencies. The second consisted of a number of antenna structures for help in evaluating the bandwidth and efficiencies of those structures. The results are indicated below.

### 2.3.1 Transmission line tests

This is a simple half wavelength coplanar waveguide resonator with embedded junctions to establish the propagation characteristics of these lines at high speed. This is important for proper design of the matching networks that will be used at these mm-wave frequencies for the intended applications. For time reasons, only one of these resonators was fabricated. But the junction I-V curve showed a distinct step at  $190 \mu\text{V}$  (and a small wiggle at  $380 \mu\text{V}$ ). This suggests a resonant frequency of  $91.96 \text{ GHz}$  [7]. The resonant structure (shown in Fig. 1) is  $500 \mu\text{m}$  long.

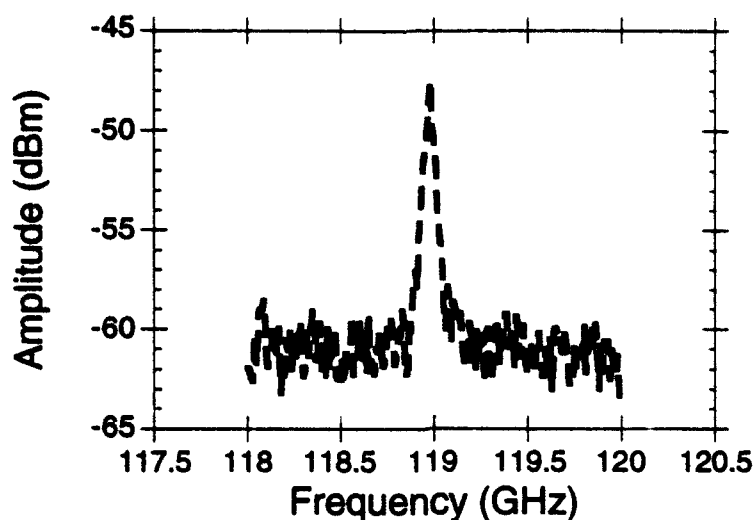
Assuming that this is  $\lambda/2$ , the effective permittivity of the structure is 10.6. This is somewhat lower than one would expect from classical coplanar waveguide formulae ( $\epsilon_{r,\text{eff}}=12-13$ ) but is not unreasonable based on some ambiguity in the electromagnetic surroundings of the transmission line. We thus have a reasonable starting point for the design of matching structures.



**Figure 1.** Coplanar waveguide structure for phase velocity tests.

### 2.3.2 Array tests and measurements

A few different array topologies have been measured extensively. The spectrum for one pure 2-D array (see definition below, having junctions both parallel and normal to the main bias current vector) operating at 77K is shown in Fig. 2. The array was embedded in a planar equiangular spiral to be described in section 2.3.4. Power was measured off-chip with a 25 dB gain horn connected to a harmonic mixer. This mixer was calibrated and connected to a conventional spectrum analyzer. The estimated accuracy on the amplitude is about 2 dB and the estimated frequency accuracy is 1 MHz.



(A)

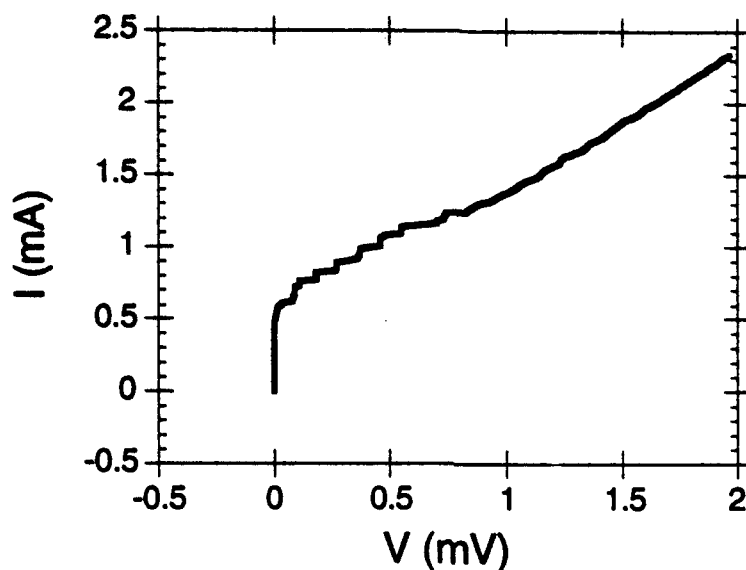


(B)

**Figure 2.** (a) Measured spectrum of a 2-D array embedded in a planar equiangular spiral antenna and (b) a photomicrograph of the interior of such an array. The dark lines ( $4\text{ }\mu\text{m}$  wide) are the upper YBCO/normal metal bilayer. The white boxes are the lower YBCO/SrTiO<sub>3</sub> bilayers. Junctions form where the dark lines cross the edges of the white boxes.

The efficiency can be calculated in a number of different ways. If a stable clock is needed, the narrow band power is of most interest and those peak values (in a 3 MHz bandwidth) are as high as  $0.3\text{ }\mu\text{W}$ . The DC input power was about  $6\text{ }\mu\text{W}$  so this corresponds to an efficiency of about 5%. Compared to efficiencies below 1% for many conventional sources, this is attractive. For other applications, it is the broadband power that is of more interest and for this array that can be as high as  $1.3\text{ }\mu\text{W}$  leading to an efficiency of 22% which is quite good. Mismatch was fortunately quite low with the present structure which helped efficiencies and output power levels considerably. The flatness of power over a broad band is not excellent, presumably because of the effects of surface wave modes. These surface wave effects are both a blessing and

a curve in that they do contribute to phase locking of the array. The many steps in the IV curve (of a typical array but not one used for efficiency calculations) shown in Fig. 3 can, at least in part, be attributed to this coupling mode.



**Figure 3.** IV curve of a 2D array at 77K.

### 2.3.3 Topological effects

One reason why 1-D arrays are not particularly attractive is that they are extremely sensitive to parameter spread. Clearly if one junction is open, the circuit will fail; but more generally, tighter parameter control is needed for phase locking than with the 2-D arrays. There are several quasi-2-D array topologies and 3 of them are illustrated in Fig. 4. A collection of 1-D arrays (Fig. 4c) will have additional difficulty phase locking because of the lower level of communication between junctions: there is only a radiation field to do the job. The pure 2-D structure (Fig. 4a) offers greater hope of phase locking with excellent power density but can suffer from the nucleation and propagation of vortices within the structure. This can artificially increase linewidth. Another structure uses inductive cross-links (Fig. 4b) as opposed to junction cross-links. It has a good deal of the phase locking advantages of the previous structure but with an impediment to vortex nucleation/motion. Spectra from these three structures [8] are shown in Fig. 5. All arrays were identical in size and used the same coupling structure. As is clear, it is difficult to get a signal out from the Fig. 4c structure and the inductive cross-link version does show the best linewidth. It should be noted that type 4b suffers more than 4a when the critical



current spreads degrade. This may be because the cross-junctions provide some negative feedback when too much current begins to be shunted away from a trouble spot. The structure of Fig. 4b, then may have the best hope for a narrow but highly lockable source for further applications assuming critical current spreads continue to improve.

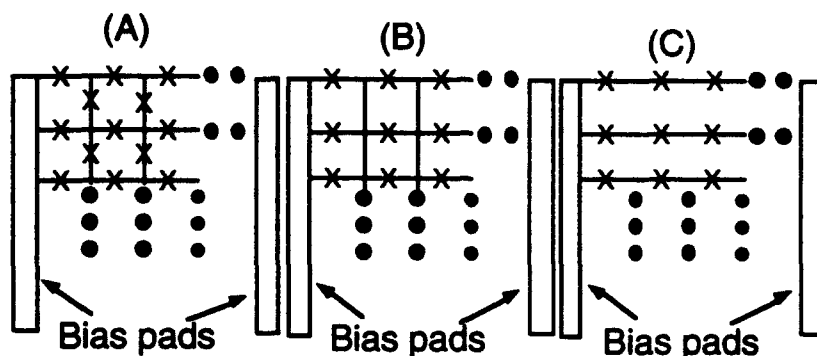


Figure 4. Three quasi-2-D structures investigated.

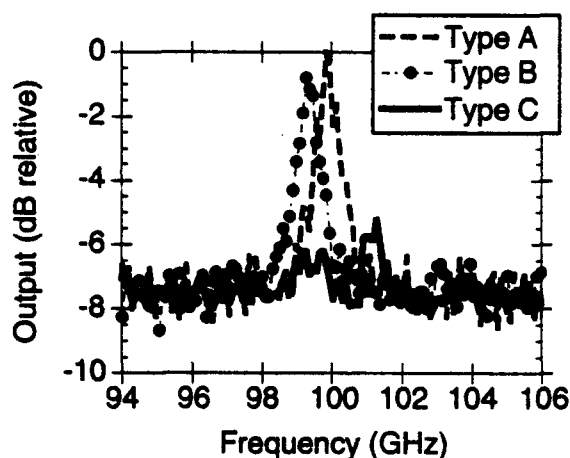


Figure 5. Measured spectra of the three array types of Fig. 3. The arrays were all identical in size with identical coupling structures.

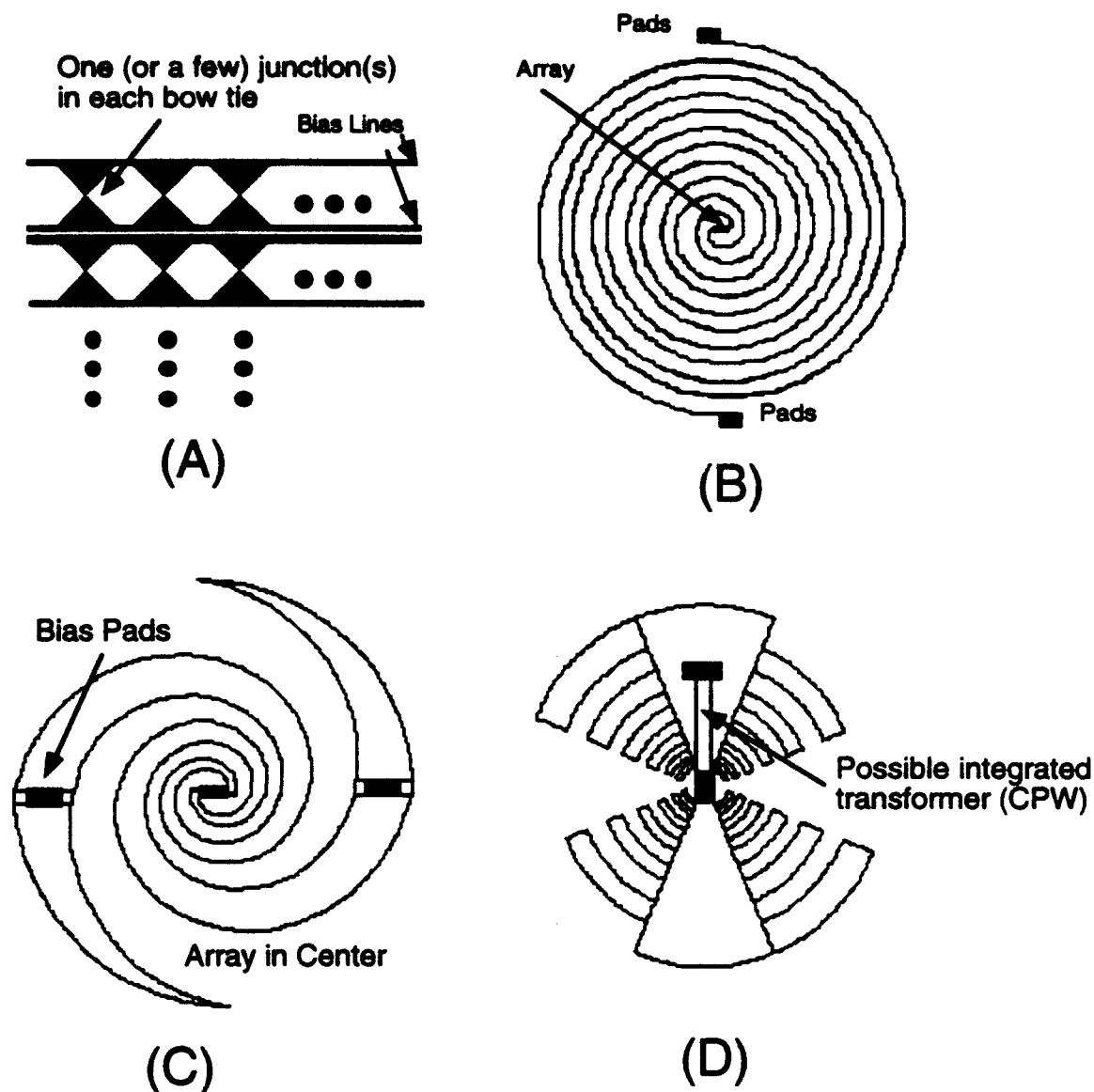
## 2.4 Radiative study and antenna runs

For many of the applications envisioned, off-chip coupling is required and there are a variety of possibilities. In narrowband situations, there are many simple alternatives but most of the applications will be broader band (an octave or more) since tunability is one of the advantages of these arrays. We considered four types of broadband antennas (see Fig. 6) [9]

(a) bow tie structures (one per junction or small groups)

- (b) Archimedian spirals**
- (c) equiangular planar spirals**
- (d) log periodic spirals**

Type (a) has been attractive for LTS arrays because of the ability to locally tune out capacitance with a minimal RF penalty. The presence of many antennas can facilitate phase locking as well. Since HTS junctions have very low capacitance, many of these advantages vanish. The bandwidth is comparatively narrower ( $\approx 2:1$  as opposed to  $4:1$  or even  $10:1$  with the others) and the space requirements can be enormous. Particularly since we are focusing on the more commercially interesting 100 GHz range, the space requirements lower the power density to a point where it is not very attractive for many applications. It is attractive, however, for the phased array application but that will be discussed in more detail in the section 2.5.4.



**Figure 6.** Four antenna types investigated. (a) array of bow tie antennas, (b) Archimedian spiral, (c) planar equiangular spiral and (d) log periodic spiral.

#### 2.4.1 Impedance

These very broadband structures all share a reasonable degree of self-complementarity. Hence, their impedances tend to approach the classical value [9] of  $\eta/2$  where  $\eta$  is the local wave impedance. For the case of an antenna on a substrate, the coplanar waveguide effective dielectric constant seems to be reasonable [9] to use when computing  $h$  which results (for  $\text{LaAlO}_3$ ) an impedance of 45-55  $\Omega$ . Experiments were done on (c) and (d) antennas on  $\text{LaAlO}_3$  and the

impedances were measured directly in the 30-40 GHz range (the lower end of the design range for the antennas used). The type (c) antenna was about  $53 \pm 3 \Omega$  over this small band while the type (d) antenna was about  $62 \pm 4 \Omega$  over this band. The uncertainty was probably more due to the complicated launch structure at the measurement point than to variations in the antenna fields themselves. The actual impedance may be slightly higher since the probe arms used for the measurement may have interfered slightly with the radiation pattern (effectively adding capacitive loading) being tested.

For nanobridge junctions, matching is relatively straightforward (even with a square array) because of the higher junction resistances. For the slightly more attractive (see section 2.1) SNS junctions, it presents more of a problem since these junction resistances are much lower. One must then consider incorporation of the matching structures in the antenna system. Type (d) has a definite advantage here since tapers or other transformer structures can be neatly fit into the interior of either apex arm.

#### 2.4.2 Bandwidth

We did not observe significant differences in bandwidth. Through simple transmission measurements between two similar antennas, it was verified that both (c) and (d) had bandwidths of at least 3:1 (30-95 GHz) but more extensive measurements were not possible within the scope of this project. Theoretically, it is expected that all would have bandwidths of up to 6:1 or higher depending on the coupling structure. Since our needs will probably not exceed 3:1 or 4:1, we suspect that this will not be a major issue. As is clear, the upper and lower frequency limits are fundamentally set by the sizes of the largest and smallest radiating elements. As such, it is reasonable to expect only minor differences between these antennas.

#### 2.4.3 Polarization

This is of more concern in the pure source application. The advantage here goes to (b) with its circularly polarized field (true to a lesser extent with (c)). Type (d) has a linearly polarized field, which is unusual but does not present a problem for transceiver applications (similar antennas on both ends). The polarization in (d) is linear but parallel to the edges of the teeth. Since the most-active tooth varies with frequency, the polarization changes with frequency more so than with the other antennas. In terms of off-chip measurement, the circular polarization is less efficient but not very position sensitive (thus making measurement much easier). The bow ties are, of course,

simpler with their direct linear polarization but this advantage will often not outweigh the other disadvantages of that approach.

#### **2.4.4 Miscellaneous**

The spirals have the advantage in terms of output power density but that is in direct competition with the matching needs discussed above. It may be possible to integrate some matching networks in the arms of the planar equiangular spiral (c), particularly if the lowest frequency needed is above 100 GHz. If any significant matching hardware is needed, the composite real estate requirements would probably favor the log periodic spiral (d).

In the measurements performed, the (d) type seemed slightly more prone to surface wave formation perhaps because of the launch polarization. While this does sometime help locking of the array, it can do strange things to the effective bandwidth.

Combining these thoughts, there are a few recommendations that can be made. When off-chip coupling is needed for the envisioned broadband applications types (b), (c) or (d) are the logical choice. For uniform illumination or when circular polarization is needed, type (c) is recommended. It has more stable impedance control than (b) and has low sensitivity to lithographic defects. For systems where matching is critical and there may be a need for integrated circuitry near the array, type (d) is a good choice. The ease of inserting a transformer and other circuits directly in the structure will keep losses to a minimum and increase efficiency (both in terms of power and real estate).

## **2.5 Subsystem design**

There are a variety of potential subsystem-level applications that may be of interests using arrays. The purpose of this section is to select the best one or two for potential work in Phase II and beyond. Among the candidates from the phase I proposal and further analysis are

- (a) illumination sources for mixing and other quasi-optical applications
- (b) a monolithic clock

- (c) a transceiver system working between chips or subsystems
- (d) a phased array antenna using individual modulated oscillators as the antenna elements

The first two on the list are similar in that only a modestly tunable source is required. The other two require a reasonable amount of ancillary circuitry (modulators, phase shifters, etc.).

### 2.5.1 Illumination sources

Type (a) is clearly attractive for mm- and sub-mm receivers possibly in the realm of radio astronomy. The criteria of interest are area of coverage, power, linewidth, tunability, polarization and its uniformity. With the variety of antennas available, the coverage area itself is not an issue but the power density is. This is the biggest weakness of Josephson array sources over competing technologies. Assuming junction uniformities continue their recent rate of improvement, a few mW may be possible from one of these sources in the near term. For sensitive mixers (SIS, RTDs and some others) this should be reasonable over a relatively large area. Linewidth may or may not be an issue and this must be traded off against tunability. Without resonant locking, the linewidths have been as low as 100 MHz in the W band range. This may be all that is needed, but some specific applications may require slightly below 1 MHz linewidths. This could possibly be achieved by improving the spreads on the junction processes. If tighter linewidths are needed, resonant locking is always available. Monolithic resonators with  $Q$ s as high as 50,000 have been reported. At this linewidth, the tuning range appears to be substantial: 3:1 bandwidths or sometimes more. Based on simple JSPICE simulations, however, getting more than 20-30% tuning range may be difficult. The trade-off here may be possible but the commercial market is somewhat limited. In this regard, the related application (b) is somewhat more attractive.

### 2.5.2 Monolithic clock

There is an increasing need for high speed clocks and one of the trade-offs discussed above may be very attractive. Modest tuning range (to adjust for clock skew or for communications synchronization) is required but huge bandwidths are probably not needed. A small linewidth would be required (resonator  $Q > 10,000$ ) but that seems possible based on present linewidths, as low as a few 10s of MHz (or lower), and available resonator technologies. Parallel plate resonators with  $Q$ s higher than this have already been demonstrated because of the low radiation

losses possible in such structures. A flip chip ground plane may be required for implementation depending on advances in multilayer technologies. The monolithic, or at worst hybrid, nature of the construct reduces power loss via surface modes and launch mechanisms. Power output in the 10s of mW range would be attractive for a number of small superconducting and other digital circuits. The tuning range would probably be at most a few GHz and that would be for global synchronization or other timing reconciliation activities.

In terms of the combination of realizability, competitiveness and economic viability, this is probably one of the more interesting applications for phase II pursuit. The cleanliness, tunability and efficiency of other sources (on a per \$ basis) including multiplied synthesizers, RTDs, Gunns and IMPATTs all seem to suffer in comparison to an array-based system.

### 2.5.3 Interchip communications

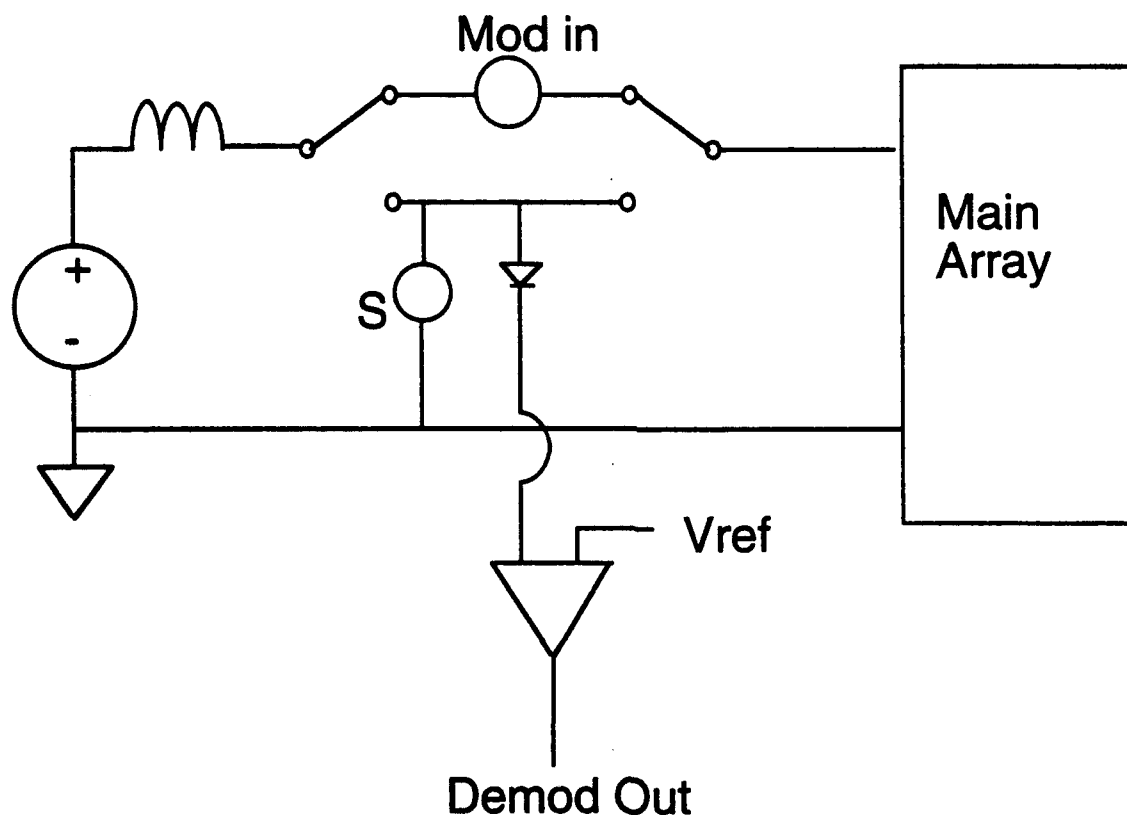
It has been proposed [10] to use a modulated mm-wave carrier as a linking medium between chips in some multichip carrier. An array would seem like a plausible choice to do such a job for a superconducting system because of its easy integrability. The antenna choice for such a system has already been mentioned but the practicality of this approach should be analyzed.

Bandwidth is the first issue of relevance. Assume a virtual carrier of 200 GHz (reliably characterizing anything higher will prove difficult and expensive) and frequency shift-keying (FSK) modulation [11]. The latter is quite simple since it relies on two sideband frequencies to represent the binary data. Other techniques may, at best, double the effective bandwidth which is probably not too important for this analysis. Linewidth is only an issue if it affects the modulation sidelobes. The values seen so far, of order 10 MHz, should be adequate.

A simple modulation and demodulation scheme is shown in Fig. 7. A dc voltage bias is applied to the array and a voltage-based data stream is applied in series during transmit. During receive, a small current bias is swept (in addition to the fixed dc bias) and envelope detected. This sweep rate is at least 3x the data rate and may be provided by a small array. The average voltage is then run through a high speed comparator circuit (semiconducting or superconducting) to pull off the output data stream.  $V_{ref}$  is defined by the FSK frequencies but will be on the order of a few

hundred mV. Tolerances will be fairly tight since  $V_{\text{ref}}$  stability will track directly into bit error rates (a stable source is hence quite important).

To determine the maximum data rate that can be handled, there appear to be two major constraints: the maximum speed of the mod/demod system and the effective bandwidth of the array system. The last question is a bit easier. We presumably can handle at least 3:1 antenna and tuning bandwidths so we will assume the available bandwidth of 200 GHz (100-300 GHz). Using a Carson estimation [11], the maximum data rate would be limited to about 0.5(total bandwidth)- frequency deviation in a one-sided sense. The highest comfortable number we could get would be about 20 GHz for a data rate (assumes a 30 GHz deviation). Modulating at 20 GHz rates does not appear to be a problem other than the time constants of the array biasing system. On the arrays tested so far via TDR, these time constants appear to be less than 15ps so that is probably not an obstacle. The envelope detection on demodulation will certainly not be a problem (50 GHz would be relatively easy) and the sweep generation will be straightforward based on the experiments above (signal levels are only in the 10s of  $\mu\text{V}$ ). Insufficient data exists on the comparator to judge the level of engineering effort required but GaAs parts exist in the literature that operate at  $> 20$  GHz and some superconducting parts operating at 30 GHz have been demonstrated. It thus seems possible that 20 GHz data rates could be practically sustained.





**Figure 7.** Mm-wave transceiver system for interchip communications. S represents a sweep source (on-chip small array) and the switches represent transmit/receive selection.

Another concern is range of transmission. It is generally difficult to get narrow beamwidth at the same time as extreme bandwidth from the antenna so we cannot expect large gain. A maximum reasonable directivity is probably about 4. Assuming a power output of  $10 \mu\text{W}$  (somewhat liberal) and a received power of at least  $0.1 \mu\text{W}$  (for reliable demodulation), the standard range equation [9] gives

$$r = \frac{\lambda}{4\pi} \sqrt{\frac{G_T G_R P_T}{P_R}} = O(3\lambda)$$

or something close to 4-5 mm. Within a stacked module pack this might be reasonable but more than that would be impractical. It would not be extremely competitive with a coaxial bump bonding approach in that case. A more attractive technological comparison would be to a fiber link but the free space range does not appear to be that high. If a better demodulation scheme could be found, such that say 1 nW power could be detected and demodulated reliably, then a few cm range would be possible.

Despite these difficulties, it should be pointed out that interchip radiation coupling is possible. As a simple experiment (to see if it could be done at all), two arrays (embedded in log periodic spiral antennas) were placed over each other, separated by about 1 mm. Array 1 was voltage biased at a fixed level while the IV curve of array 2 was measured. The concept was that if radiation was being coupled, a step should appear on the IV curve of array 2 that tracked with the bias on array 1. The IV curve of array 2 while array 1 was biased at  $150 \mu\text{V}$  is shown in Fig. 8. The step was found to track the array 1 bias over the range 120-245  $\mu\text{V}$ , decreasing in size and vanishing at both ends of that range. The step is somewhat broader than expected because of excess noise pickup in this rather complicated experimental setup. While this certainly does not demonstrate the practicality of the subsystem, it does illustrate that interchip coupling is possible.

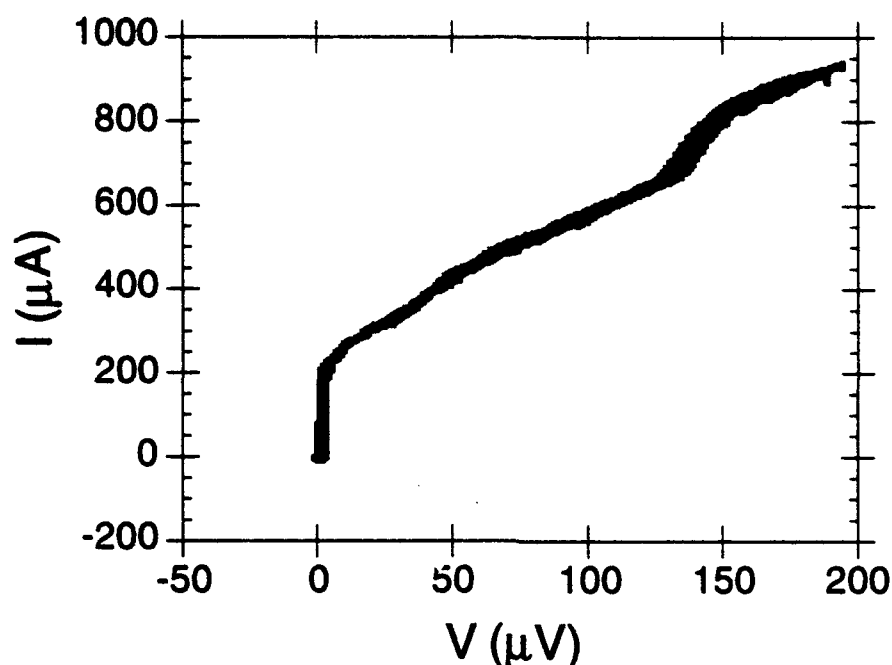


Figure 8. I-V curve of an array (in a log periodic antenna) placed 1mm above a voltage biased array in a similar antenna.

#### 2.5.4 Phased array

A phased array system is potentially attractive in the context of an illumination source or a short range transponder. With a carefully controlled phase lag between elements of the array some steering would be possible. Although the probable beamwidth will be large, steering would enable some selection between destinations. As mentioned earlier, a likely topology is one of individual radiating elements (e.g., bow tie antennas with a small array at each) steered in phase with respect to the others. The use of Josephson inductance to do the tuning is one choice for size reasons although other options include a ferroelectric capacitance or a flux flow inductance modulation. Linewidth requirements would not be severe (at least among the envisioned applications), the present values would probably be adequate.

Consider first what the phase control element would be. With a JJ inductance unit, a few pH of shift would be quite realizable. An artificial transmission line phase shifter would then allow more than adequate steering over a large bandwidth at the price of real estate. It is likely that a single tuning element is all that would be allowed for that space reason. Based on recent analysis

[12], it seems that getting the needed steering from a single Josephson element would be very difficult. The same would hold for a single flux flow element since the scale of inductance changes are about the same. A small ferroelectric capacitor would be possible but the materials integration issues would be significant. Aside from the needed steering capability, the control wiring would be a significant problem. Because the number of elements will be large for sufficient power levels, small arrays would probably be used for each radiating element. Getting the control wiring to each radiating element without interfering with the radiation pattern would be difficult and almost certainly would result in a slow steering system (many ms probably).

In addition to the above problems, simulations suggest there will be difficulty in maintaining sufficient phase lock in the array with the steering differentials in place. It is likely that there would be severe amplitude fluctuations with steering angle greater than about 10 degrees with a center frequency of 100 GHz. If that level of steering is not adequate, some fairly substantial amplitude trimming circuits will have to be incorporated at each element as well. Since the real estate and control wiring space is already somewhat limited, this represents a fairly severe problem. Combining these obstacles, it would appear that the phased array system is a more long term project requiring more significant development than some of the other subsystems with significantly greater commercial appeal.

### *2.5.5 Conclusions on subsystem applications*

The most enticing subsystem demonstration appears to be in the area of a monolithic clock. It is an application of considerable commercial impact, marries well with the military source needs, requires minimal active circuit or materials development outside of the array proper and takes maximal advantage of the benefits of array-based oscillators. The apparent advantages in efficiency, size, integrability and tunability make the clock concept quite attractive for short term development. While many of the other applications have advantages, they all have some significant limitations in terms of technology development required or in perceived advantage over competing approaches.

## 2.6 References

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### **3 Publications:**

Two papers based on the work in this program have been published. They are references 3 and 4 above whose listing is repeated below.

J. S. Martens, A. Pance, K. Char, L. Lee, S. Whiteley, and V. M. Hietala, "Superconducting Josephson arrays as tunable microwave sources operating at 77K," Appl. Phys. Lett. **63**, 1681 (1993).

J. S. Martens, K. Char, A. Pance, L. P. Lee, M. E. Johansson, S. R. Whiteley, K. E. Kihlstrom, J. R. Wendt, V. M. Hietala, T. A. Plut, G. A. Vawter, S. Y. Hou, Julia M. Phillips, and W. Y. Lee, "The use of 2-dimensional arrays to determine the uniformity of Josephson junctions," IEEE Trans. on Appl. Superc. **3**, 3095 (1993).

### **4 Personnel:**

#### **Jon Martens**

##### **Current Position:**

Member of the Technical Staff

##### **Education:**

Ph.D., Electrical Engineering, University of Wisconsin

##### **Experience:**

**Dr. Martens has a background in microwave/mm-wave circuit and device design and has been working on high speed superconducting electronics for the last 5 years. This includes work on Nb and HTS circuits at the University of Wisconsin and high speed HTS circuits at Sandia National Laboratories. The latter includes assisting in the development of two HTS junction technologies, the demonstration of HTS digital circuits, the development of the flux flow transistor to the stage of W-band amplification and the development of novel mm-wave materials characterization techniques. At Conductus he has worked on HTS digital and analog Josephson circuits (including a demonstration of HTS single flux quantum logic circuits), junction development and mm-wave measurements.**

## **Aleksandar Pance**

### **Current Position:**

Member of the Technical Staff

### **Education:**

Ph.D., Electrical Engineering, University of Rochester

### **Experience:**

Aleksandar Pance joined Conductus after finishing his Ph.D. at the University of Rochester. His Ph.D. thesis deals with modeling, design, analysis and measurements of 2-D quasioptical Josephson junction arrays for 100 GHz-1 THz oscillators. He has performed microwave model measurements and characterization of 2-D active grid antenna arrays and numerical simulations of Josephson junction arrays in time domain. He has designed 2-D quasioptical arrays with 1000-1100 junctions for fabrication in Nb-based technology. He has proposed new Central frequency/Wideband design of quasioptical Josephson oscillator arrays with integrated tuning structures. Dr. Pance is currently involved in several projects dealing with both digital and analog high frequency applications of low and high temperature superconductors.

## **Kookrin Char**

### **Current Position:**

Manager, Device Development group

### **Education:**

Ph.D., Applied Physics, Stanford University

M.S., Physics, UCLA

B. S., Physics, Seoul National University

### **Experience:**

Kookrin Char has been responsible for thin film and device development based on pulsed laser deposition at Conductus since joining the company. He has designed and constructed a mullet-target laser deposition system whose target carousel has recently become a commercial product. He has developed processes for depositing state-of-the art YBCO films on buffered sapphire substrates. His multilayer technique has been successfully applied to produce engineered Josephson junctions in high-quality films. He leads the team that has developed the bi-epitaxial Josephson junction technology now in use at Conductus and is responsible for many of the key innovations behind Conductus' HTS JJ technology. Recently, he developed epitaxial HTS SNS Josephson junctions using  $\text{CaRuO}_3$  as the metallic barrier. At Stanford University, he developed highly-successful mullet-source sputtering techniques for producing YBCO films and identified the existence of the "2-4-8" phase in these films. He also pioneered many techniques for processing YBCO films. Kookrin Char has maintained a position of leadership in high-temperature superconductor thin film materials and Josephson junctions since the earliest days of this new technology.



## **Marie Johansson**

### **Current Position:**

Process Engineer

### **Education:**

Graduate courses (physics), University of Colorado, Boulder, 1990-1991

Graduate courses (physics), University of Linköping, Sweden, 1988-1989

BS, physics, University of Linköping, Sweden, 1986

### **Experience:**

Ms. Johansson joined Conductus Inc. in July 1992. She is responsible for process development and production of microwave and MRI/NMR devices at Conductus. She has developed a reproducible wet-etching and passivation technique for processing of these devices. During her time at Conductus, she has also developed a processing technique for digital devices such as shift registers, and analog/digital converters.

From 1989 to 1991, as a guest researcher at National Institute of Standards and Technology, she developed a process for fabrication of SNS junctions, from high temperature superconducting thin films. Ms. Johansson also performed deposition and characterization of these materials. From 1991 to 1992 she was employed at Advanced Fuel Research, East Hartford CT. where she was responsible for establishing the processing of YBCO IR-detectors on Silicon. Ms. Johansson was employed in the Microwave Technology Group at the National Defense Research Institute (FOA), Linköping, Sweden from 1986 to 1989. She developed, fabricated and characterized passive microwave devices (based on normal metals). She was responsible for the development of a low loss 3dB coupler for use in microwave systems.

## **Stephen Whiteley**

### **Current Position:**

Manager, Digital Technologies group

### **Education:**

Ph.D., Electrical Engineering and Computer Science, UC Berkeley

### **Experience:**

Stephen Whiteley has an extensive background in superconductor and semiconductor circuit development. Most recently he has served as a consultant to several firms pursuing superconductive electronics development, particularly in the area of advanced signal processing components. He is currently developing an advanced Josephson circuit simulator based on SPICE3 as a commercial product. He served as the manager of the New Devices and Circuits Group at Hypres, Inc., where he designed complex Josephson circuitry that was often integrated with optical and other sensors. Upon completion of his doctorate, he worked for Tektronix, Inc. on designing a high-speed analog/digital bipolar LSI integrated circuit -- a time interpolator -- that is currently in use in the company's products. Stephen Whiteley's participation brings one of the foremost experts currently working in this field into the project.

### 5 Interactions:

Talk presented below contained array material (the use of NBJ arrays to help determine uniformity):

"Electron beam defined nanobridge junctions: uniformity, physics and applications," 1993 Fall MRS meeting, Boston, MA, 11/29/93-12/3/93.

Paper below was exclusively on this array work:

"HTS Josephson arrays," 1993 International Superconducting Electronics Conference, Boulder, CO, 8/12-14/93.

### 6 New discoveries

We believe that the experimental comparison of the effects of 2-D array topology on spectral performance (section 2.3.3) is original. This provides direction for the proper array design to be possibly exploited in Phase II and other work. It is also believed that the modulation/demodulation system proposed for the transceiver application (section 2.5.3) is a new concept. It provides a monolithic circuit approach to interchip communications at 20 GHz data rates although admittedly of limited spatial range.

### 7 Future thoughts

Based on the experiments to date, it appears that HTS technology is quite capable of producing Josephson arrays with reasonable linewidths, modest output power, good efficiency, straightforward antenna coupling and excellent tunability. The junction processes are still improving and as the critical currents and their uniformities improve, it is likely that output power densities and linewidths will improve as well. For a phase II project or other follow-on work, a subsystem integration is of great importance. There are a large number of circuits (drivers, modulators) and radiative structures to facilitate this. The subsystem to pursue should probably be selected on the basis of the maximal advantage of a Josephson system (efficiency, tunability, potential linewidth control, size) and maximum commercial value. Of those subsystems evaluated, the quasi-monolithic clock seems to be the most attractive. Assuming that

the linewidth specifications discussed in section 2.5 can be achieved and power densities increase a small amount, a very useful circuit could be produced that would satisfy the needs of a number of digital signal processing and communications systems under consideration.